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BED MATERIAL TEXTURE IN LOW ORDER STREAMS ON THE QUEEN CHARLOTTE ISLANDS, BRITISH COLUMBIA

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ABSTRACT

Low order channels comprise a large proportion of the links of every drainage basin, and are often at the centre of land management concerns. They exhibit hydrological and geomorphological characteristics atypical of higher order links. This paper examines the nature and causes of variations in the bed material texture of two streams on the Queen Charlotte Islands, British Columbia. The extant, functional exponential model is found to be inadequate for explaining observed changes in grain size parameters with distance downstream. Recurrent disruption of sediment transport by large organic debris jams, and the sporadic contamination of the fluvial sediment population by colluvial inputs, preclude the development of longitudinal structure. Rather, grain size varies erratically over short distances. A stochastic model best describes the observed variations, and should be adopted as an alternative to the exponential model in low order links. Characteristic variances are controlled by the degree of hillslope–channel coupling, and the extent and characteristics of non-alluvial storage mechanisms.

KEY WORDS bed material texture; low order channels; hillslope–channel coupling; large organic debris; stochastic variability

INTRODUCTION

From Horton's law of stream numbers (Horton, 1945; Shreve, 1966) it is clear that low order channels comprise a large proportion of the links in any drainage basin. They are the origin of the drainage net, grading into the adjacent, unchannelized land surface. Consequently they are often the major locus of erosional work, and the major sources of sediment to the downstream system. Interest in headward links, often because of fisheries, timber and recreational resource management concerns (Beschta and Platts, 1986), has indicated that they exhibit hydrological and geomorphological characteristics atypical of higher order links (Miller, 1958; Heede, 1972; Newson, 1981; Lisle, 1987). This paper examines the consequences of this for bed material texture, with particular reference to low order channels on the Queen Charlotte Islands, British Columbia.

Of special relevance is the observation that the supply and storage of streambed sediments is often 'non-alluvial'. Supply is not always by fluvial transfers from upstream, and storage is often controlled by roughness elements other than alluvial deposits. An understanding of the variability of bed material texture in small coastal streams in the Pacific Northwest has implications for salmonid habitat monitoring and assessment programmes and, in a wider context, for modelling grain size changes at the drainage basin scale (Rice, 1994; 1995).

LOW ORDER STREAMS

Non-alluvial sediment storage and supply in headward links

Within the headward links of a drainage net a high degree of hillslope–channel interaction is likely. Stream channels lack a buffering alluvial floodplain (Newson, 1981) and are frequently in close proximity to active

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colluvial transfers. At any point there is a high probability that stream bed sediments have been supplied by local creep and episodic mass movement processes. Reciprocally, sediment production on the hillslopes is in part associated with fluvial activity at the base of the slopes. Such streams may be described as strongly coupled to the adjacent land surface (Church, 1983). Harvey (1987, 1991) has examined the implications of such coupling for channel morphology in upland Britain. Hogan (1989) and Benda (1990) have shown that such coupling can dominate stream channel morphology in headwater streams in the Pacific Northwest. Whiting and Bradley (1993) have proposed a classification system for headwater streams which is highly dependent upon the characterization of hillslope–channel interaction.

Associated with coupling in headward links is the presence, in the channel, of flow boundaries and roughness elements that are not of alluvial origin. Bedrock is generally close to the surface, large boulders of colluvial origin are common and, in forested areas, large organic debris (LOD: logs, limbs and root-boles >10 cm in diameter) is supplied in abundance by debris flows, debris slides, bank erosion and blowdown. Fans and other depositional forms associated with mass movements and steep tributaries may be present in valley bottoms.

Fluvial sediment deposition is often controlled by the geometry and trap efficiency of these elements, their role in dissipating stream energy, and their effect on local water surface slope and flow patterns (Swanson *et al.*, 1976; Lisle, 1986; O'Connor *et al.*, 1986; Carling, 1989). Sediment storage is not then determined by the reciprocal relations between flow hydraulics and a mobile channel boundary. Heede (1972) described LOD as 'inflexible', because it does not respond to flow conditions in the same way that alluvial roughness elements (bars and bedforms) do. Rather, non-alluvial boundaries and obstructions introduce complex flow structures (Furbish, 1993), and invalidate the basic assumption of channel self-formation (Lisle, 1987).

The arrangement of fluvial sediment accumulations along the channel is then predisposed to reflect the location and spacing of non-alluvial elements, rather than some scaling of the flow and sediment properties of the channel. Where immobile colluvial boulders and bedrock obstructions are the primary non-alluvial elements, their distribution along the channel and the resulting location of stored sediments will tend to be irregular. This is indicated by the absence of well-defined pools and riffles in Miller's (1958) study of high mountain streams in New Mexico. The nature of the relation between LOD characteristics and pool–riffle spacing is not clear, but the distribution of LOD reflects both input processes (windthrow, bank erosion, landslides) which are presumably distributed randomly along the channel, and subsequent redistribution of LOD by debris flows and floods. The spacing of sediment accumulations is again atypical: a shortened pool–riffle periodicity of two to four channel widths (cf. five to seven widths) has been reported for forested, coastal streams in the Pacific Northwest (Lisle and Kelsey, 1982; Hogan, 1986; Nakamura and Swanson, 1993). Hogan (1989) found that jam spacings along Riley Creek on the Queen Charlotte Islands are skewed, with an average jam spacing of one per eight channel widths, a standard deviation of eight channel widths, and a modal class of three channel widths.

The impact of coupling and non-alluvial storage controls can be expected to decline downstream as a consequence of the downstream increase in the magnitude of fluvial activity relative to hillslope activity. With increasing discharge the stream acquires the power to remove and assimilate non-alluvial sediments and obstructions. As fluvial sediment discharge increases, the relative impact of colluvial contamination diminishes and floodplain deposits accumulate. These buffer the active channel from hillslope inputs and reduce the occurrence of bedrock controls. As the channel widens, large organic debris becomes less abundant (Keller and Swanson, 1979) and less significant because of its diminishing size relative to the channel (Bilby and Ward, 1989). Depositional fans become less obstructive where tributary gradients decline and the main stem is competent to rework tributary sediment yield.

It is difficult to make generalizations about the rate at which these factors become less important downstream. While relatively strong coupling is evident in the headwaters of all drainage basins which transport sediment, intermittent coupling may extend into distal reaches. Drainage basin morphometry, biophysical conditions and geomorphological history (particularly, in northern regions, the legacy of Pleistocene glaciation) are important in this respect.

Sediment texture in strongly coupled channels: a hypothesis

Theoretical arguments (e.g. Parker, 1991) and empirical evidence (e.g. Shaw and Kellerhals, 1982) suggest that, in the absence of tributaries, grain size declines systematically in a downstream direction. Abrasion, and selective entrainment and deposition, have been identified as the processes responsible for this diminution (Sternberg, 1875; Krumbein, 1942). Both processes are supposed to yield a negative exponential reduction in grain size with distance downstream. However, the relative importance of each process remains unresolved (see Werrity (1992) and Mikos (1993) for reviews), and a negative exponential model, $D = D_0\,e^{-aL}$ (where D is grain size at distance L downstream, D_0 is initial grain size and a is a coefficient representing both abrasion and sorting), has been used functionally to describe the undifferentiated effects of both processes within channel links (Church and Kellerhals, 1978; Knighton, 1980).

'Grain size' is usually taken to be some percentile or moment of the cumulative distribution, and calibrations of the model therefore yield values of a that are in part statistical artifacts of the sediment distributions investigated. The resulting equation describes the empirical changes in the chosen statistical parameter rather than the amount of wear on, or the differential transport of, individual size fractions. While physical understanding of downstream changes in grain size is not enhanced by this approach, it provides a straightforward way of describing textural modification.

There is evidence in the literature to suggest that coupling and non-alluvial storage controls have a significant impact on the pattern of variation in streambed sediments. Following the largest flood on record at the time, Krumbein (1942) studied the texture of deposits along Arroyo Seco, a headward tributary of the Los Angeles River in the San Gabriel mountains of southern California. He identified 'log and boulder jams', bedrock constrictions, and tributary-mouth cones as significant determinants of local grain size in the main stem, and there was evidence that debris flows and landslides introduced large amounts of colluvial material to the stream. The observed pattern of grain size variation was erratic and there was no overall change in grain size along the study reach. In his study of mountain streams in the Sangre de Christo Range, Miller (1958) found that grain size did not exhibit any consistent pattern with distance downstream. He attributed much of the observed scatter to the delivery of fresh rock from outcrops in or near the channel. MacPherson (1971) reported an overall downstream decline in grain size along Two O'Clock Creek, a short, steep tributary of the North Saskatchewan River in the Canadian Rockies. Scatter about the relation is very high, however, the negative exponential model explaining only 24 per cent of the total variance. MacPherson reported that the persistent delivery of fresh colluvium and till, which mantle the steep slopes of the basin, is probably responsible for this variance. Knighton (1975) commented that mean grain diameter is highly variable in the headwater areas of the river Dean (Cheshire, U.K.), as a result of irregular sediment supply. Along the length of several small streams on the Queen Charlotte Islands, Hogan (1986) documented the highly variable nature of surface grain sizes and suggested the importance of LOD as a control. Working in central Oregon, Benda (1990) emphasized the stochastic nature of coarse sediment supply to stream channels by debris flows, and the resulting variability of bed material texture.

It is hypothesized here that non-alluvial sediment supply and storage preclude the systematic diminution of sediment texture in headward links. Specifically, spatially and temporally frequent colluvial inputs (consisting of heterogeneous, disparate grain size distributions) and local sorting around non-alluvial storage controls mask the effects of longitudinal sorting and abrasion processes. This hypothesis is tested using data from two streams on the Queen Charlotte Islands, British Columbia.

STUDY AREA

The study area is located on the steep western edge of the Skidegate Plateau on Graham Island, approximately 150 km off the northwest coast of British Columbia (Figure 1). Climate is perhumid marine, with annual precipitation between 3600 and 5000 mm. The Islands lie within a Pacific westerly storm track and intense rainfall and destructive winds are common (Alley and Thompson, 1978). The major geological formations (Masset and Yakoun) consist of deeply weathered, fissured and jointed soft volcanic and sedimentary rocks (Sutherland Brown, 1968). A thin cover of till and soil, generally less than 1·0 m thick,

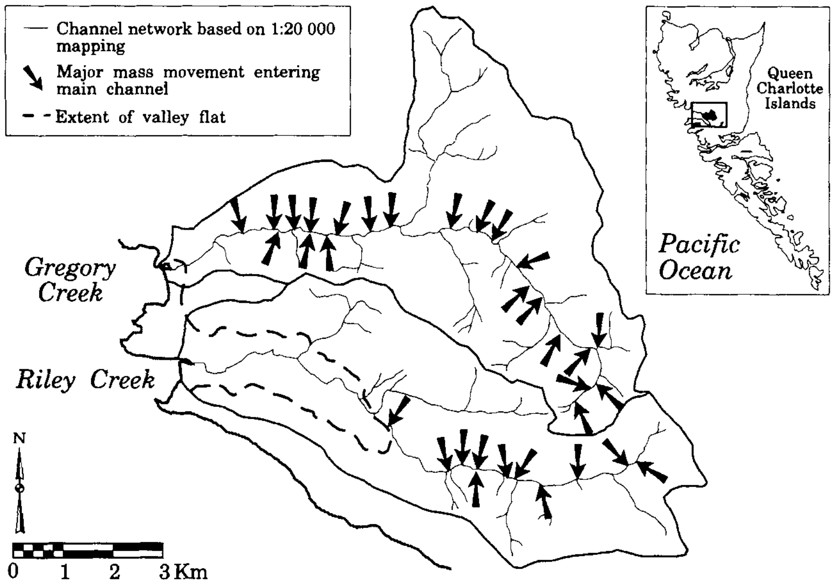

Figure 1. Study area. The indicated valley flat buffers the lower portion of Riley Creek from colluvial inputs. Mass movement information courtesy of Schwab and Hogan (pers. comm.)

mantles glacially oversteepened slopes and supports an old-growth forest of Western Hemlock (*Tsuga heterophylla*), Western Red Cedar (*Thuja plicata*) and Sitka Spruce (*Picea sitchensis*). Seismic activity along the Queen Charlotte fault is common.

These conditions promote a high rate of sediment production and rapid mass wasting (Roberts and Church, 1986). Gimbarzevsky (1986) estimated an average major slope failure frequency of $1{\cdot}0\,km^{-2}$ over the entire land mass. Rood (1984) estimated that of the total volume of sediment mobilized by mass wasting, an average of 43 per cent directly enters stream channels, testimony to the strong coupling throughout the small ($<50\,km^2$), steep, low-order drainage networks characteristic of the islands. Additional colluvial material is delivered to the stream system by bank erosion and creep (Roberts, 1987). Estimates of total sediment input to four undisturbed creeks made by Roberts (1987) vary between 71·6 and $170{\cdot}2\,m^3\,km^{-1}\,a^{-1}$.

Channelized debris flows and debris slides introduce large amounts of LOD. The volume of LOD in the channel varies from 0·03 to $0{\cdot}06\,m^3\,m^{-2}$ (Hogan, 1986). Accumulations of LOD, or log jams, are common, with a modal spacing of one per 90 m (three to four channel widths) in the reaches studied. Channel stability and morphology strongly depend on the spatial arrangement and temporal dynamics of these log jams (Hogan, 1989), and they dominate sediment storage.

Surveys of surface and subsurface bed materials were conducted in Riley Creek and Gregory Creek, adjacent streams which drain into Rennell Sound. These are third- and fourth-order streams, respectively, according to the blue-line network on 1:20000 topographic maps (both second order on published 1:50000 maps of the National Topographic Series). Relative relief and mainstem channel length are 840 m and 11·0 km in both cases, and the drainage basin areas are 28·3 and $35{\cdot}5\,km^2$. The entire length of Gregory Creek and the upper part of Riley Creek are strongly coupled. However, a valley flat in the lower 4·2 km of Riley protects the channel from hillslope failures and other colluvial sediment inputs. This provides an opportunity to assess the influence on textural variation of a buffering valley flat. Major failures (greater than 1·0 ha in area) have been mapped (Figure 1) and dated using dendrochronological techniques (Schwab and Hogan, pers. comm.). Of the 11 failures that affected the main channel of Riley Creek, none occurred within 5·8 km of the mouth.

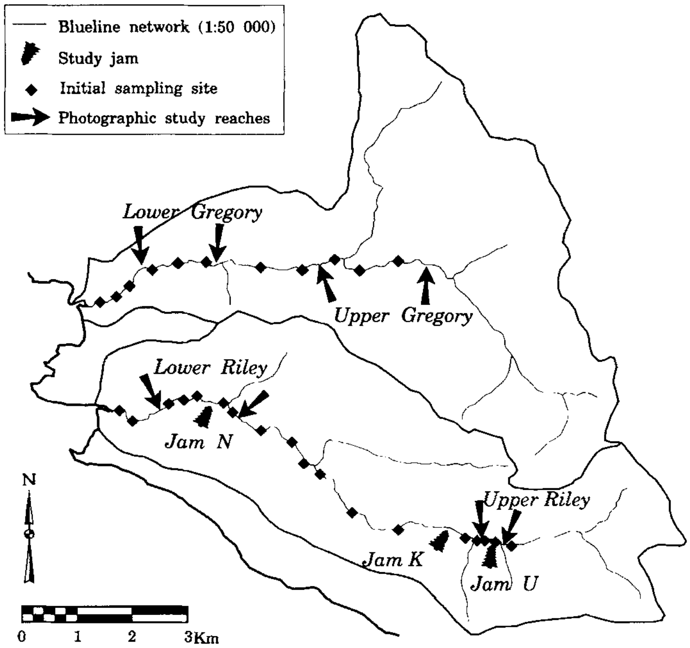

Figure 2. Initial sampling sites, photographic survey reaches, and study jams U, N and K

In many other respects (geology, climate, morphometry) the two basins are similar, such that the nature of geomorphic activity and the textural composition of weathered materials are expected to be similar. However, 14 per cent of Riley and 2 per cent of Gregory have been clear-cut. Given the potential impact of forest harvesting on sediment production (Swanston and Swanson, 1976; Schwab, 1983; Rood, 1984) and on the abundance, size and in-stream arrangement of LOD (Hogan, 1986), the contrasting land-use histories may affect the pattern of textural variation. Ten years after the cessation of logging, however, surface median grain size is not significantly different between the two streams, and the pattern of variability within each creek does not appear to be affected by the contrasting land-use.

METHODS

Grain size information

Horizontal winnowing and vertical infiltration lead to the exposure at the surface of only the coarser particles present in the bed. Surface material is therefore a more critical indicator of downstream change, because the average size is not attenuated by ubiquitous interstitial fines. If systematic changes are not found in the surface data, it is reasonable to judge that subsurface material is unlikely to vary systematically. It is therefore expedient to consider surface materials and, although subsurface material was collected and analysed for fisheries quality, it is not reported here (see Rice, 1995).

Sampling sites were selected independently of log jam positions and colluvial sediment sources in each of seven links. It is necessary to consider links as the focus of this work in order to discount the well documented (Miller, 1958) discontinuities in bed material texture associated with tributary confluences. Riffle–pool breaks (the upstream portion of the riffle) were consistently sampled in order to minimize local-scale variability (Wolman, 1954; Church and Kellerhals, 1978). In particular, this strategy precludes the study of sediment texture variation at riffle–pool and finer scales. In an initial survey during 1989, standard sedimentological techniques (Kellerhals and Bray, 1971) provided information about surface texture at a total of 31 mainstem sites (Figure 2). The Wolman method was used to collect 100-stone samples along

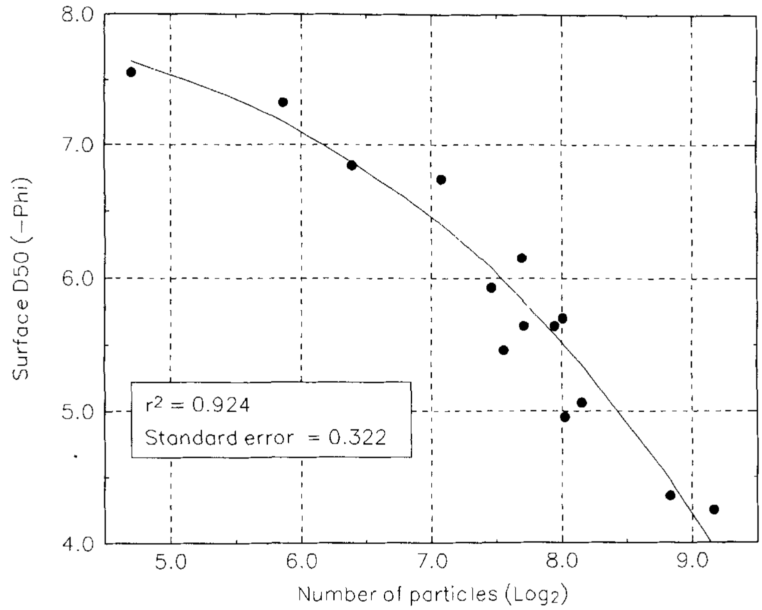

Figure 3. Photo calibration curve. The curve relates number of particles per 0·25 m^2 to measured surface median grain size, and was fitted by eye. The standard error of the y estimates and r^2 are noted. Number of particles is presented as $\log_2$ to provide consistent scales

riffle-top transects. Clasts finer than 8 mm were excluded because of the inability of operators to consistently manipulate such material in flowing water. The conventional b-axis measurement was used to define grain size distributions in half-phi classes.

In order to determine a within-site variance term, eight 100-stone samples were randomly divided into two 50-stone replicates. Bray (1972) recommended that a consistent estimate of mean size requires at least 50 stones. For each pair, the difference in median size and the variance of these medians were determined. The mean difference was found to be 3·7 mm and the mean of the variances 7·6. The analysis was repeated for phi units, yielding a mean difference of 0·12 phi and a mean variance of 0·0104. The latter is used as a within-site variance term in subsequent analysis. Since 50-stone samples will yield less consistent estimates of a population characteristic than 100-stone samples, it ought to be conservative.

A photographic survey, conducted in 1990, provides a detailed picture of the variations in surface material in two reaches in each stream. All of the bars in the four reaches were sampled, providing bar-to-bar scale information over distances of 0·28 and 1·42 km in upper and lower Riley, and 1·89 and 1·78 km in upper and lower Gregory. These distances represent 2·9, 18·5, 27·6 and 20·8 per cent of the surveyed channel lengths respectively. The method is based on establishing an empirical calibration of median grain size to the number of particles in a given area on the bed surface (Church *et al.*, 1987). A standard area, delineated by a 1·0 m^2 quadrat, was photographed at a total of 130 sites. In each case the quadrat was placed adjacent to a riffle–pool break, close to the water's edge. At 14 of these sites, direct measurement of 100 stones within the quadrat allowed the construction of a calibration curve. The non-linear relation shown in Figure 3, fitted by eye, has the highest coefficient of determination (r^2 = 0·92) and lowest standard error of any of several relations tried. The deviation of this curve from the theoretically anticipated negative square root function is probably related to the higher potential for counting errors as grain size declines.

Log jam studies

Various characteristics of all of the log jams in the photographed reaches were assessed semi-quantitatively using the classification scheme of Hogan (1989). This provides information about jam age,

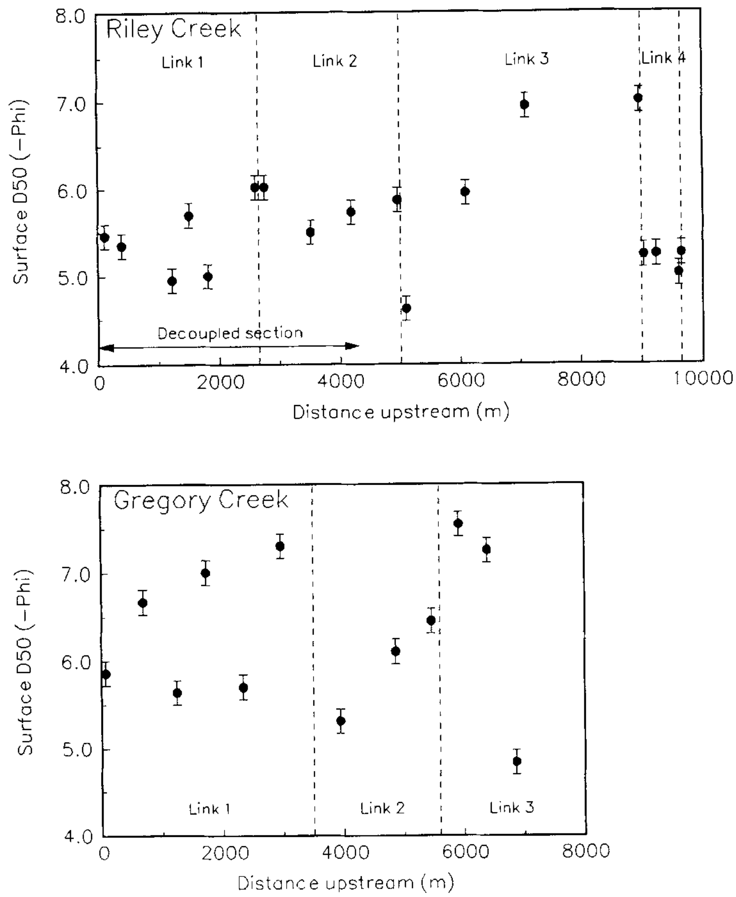

Figure 4. Initial survey data with 95 per cent confidence limits. An exponential series would be indicated by a linear trend. Vertical lines denote blue-line tributaries

integrity, lateral extent, upstream sediment storage and breaching channels. In order to obtain a better understanding of how log jams affect texture at a local scale, three jams in Riley Creek were considered in some detail. They were selected on the basis of different ages and morphologies in order to reflect a cross-section of possible jam types.

During at least part of their existence, jams have the potential to influence sediment texture from bank to bank. The texture of the entire bed in the vicinity of the jam, which may include several facies, is therefore of interest. Wolcott and Church (1991) have shown that the general characteristics of a unit consisting of several facies is adequately described by one large sample which is the aggregate of numerous, small samples located randomly throughout the unit. This pooling method was used to characterize bed material upstream and downstream of each jam.

Sediment transfers through the three jams (jam permeability) were assessed using two methods. The riffles immediately upstream of each jam were seeded with magnetically tagged fibre-glass 'stones' (see Hassan *et al.*, 1984). The transfer of these stones to the downstream side of the jam over the winter season provided a measure of permeability. A deployment of distinctively coloured stones downstream of each jam provided an estimate of the ambient transport in the local reach. As an adjunct, scour chains were positioned around two of the jams to assess relative aggradation and degradation over the winter of 1989–1990. Details can be found in Rice (1995).

Table I. Within-link variance of surface D_{50} (phi units)

Link	σ_B^2	n_1	σ_W^2	n_2	F†
Riley					
1	0·168	6	0·0104	8	16·15***
2	0·049	4			4·71**
3	1·242	4			119·42***
4	0·015	3			1·44
Gregory					
1	0·519	6	0·0104	8	49·90***
2	0·341	3			32·79***
3	2·207	3			212·21***

† F is the ratio of between-site variance (σ_B^2) to within-site variance ($\sigma_W^2 = 0{\cdot}0104$ with 8 d.f.). Within-link variances are significant when accompanied by one or more asterisks: ***, significantly different at $\alpha = 0{\cdot}01$; **, significantly different at $\alpha = 0{\cdot}05$. *, significantly different at $\alpha = 0{\cdot}10$. No asterisk indicates that within-link variations are not significant at $\alpha = 0{\cdot}10$. This table succeeds Table 8.1 in Rice (1994)

RESULTS AND DISCUSSION

The nature of textural variation

Initial survey surface D_{50} data are plotted in phi units against distance upstream in Figure 4. The mean standard error of the eight replicate pairs discussed above was used to calculate the 95 per cent confidence intervals shown. Formal statistical analysis (Table I) indicates significant between-site variations within six of the seven links. However, only in link two of Gregory is a systematic, clearly exponential trend apparent (Figure 4). In general the data are erratic, and in one case there appears to be systematic downstream coarsening. In light of the limited number of data points, it is possible to interpret a perturbed exponential signal in several links, but it is clear that there is no consistent pattern of within-link change at this resolution.

The higher resolution photographic data provide a more detailed picture. Surface median grain size estimates for the four reaches are presented in Figure 5. In each case grain size varies considerably and erratically over very short distances. Large discontinuities are apparent and are not related to tributaries except at the head of the Lower Riley reach. Bar-to-bar variations in D_{50} of 1–4 phi units (typically 32 to 120 mm) are common, especially along Gregory Creek. The standard error of the photograph calibration curve (0·322 phi) reflects the imperfect relation between particle count and median grain size. The sampling error due to positioning of the quadrat within the bar head is estimated by the split stone counts discussed above (0·0104 phi). The pooled variance, (0·1036 + 0·0104 = 0·1140) is used as a within-site term to test the significance of between-site variations in the photographic data. Of the four reaches, between-site variance is lowest in Lower Riley and is equal to 0·329 phi units. An F-test shows that this is significantly greater than the within-site term at $\alpha = 0{\cdot}05$ (41 and 13 d.f.), indicating that the bar-to-bar fluctuations observed in all four reaches are significant.

The photographic data confirm that the disorder apparent in the initial survey exists at a bar-to-bar scale. It is clear that surface D_{50} does not vary systematically in these low-order streams. Indeed, it appears that D_{50} varies randomly between like sedimentary units.

The effect of coupling on variability

Assessing the effect of individual colluvial inputs is challenging because they are numerous and difficult to isolate. However, the effect of coupling can be studied by comparing the variability of texture within the coupled reaches with that within the decoupled reach. While upper Riley and the entire length of Gregory are intermittently supplied with poorly sorted, heterogeneous, colluvial material, lower Riley is largely dependent on fluvial transport for its sediment (several non-fluvial bank exposures are apparent along

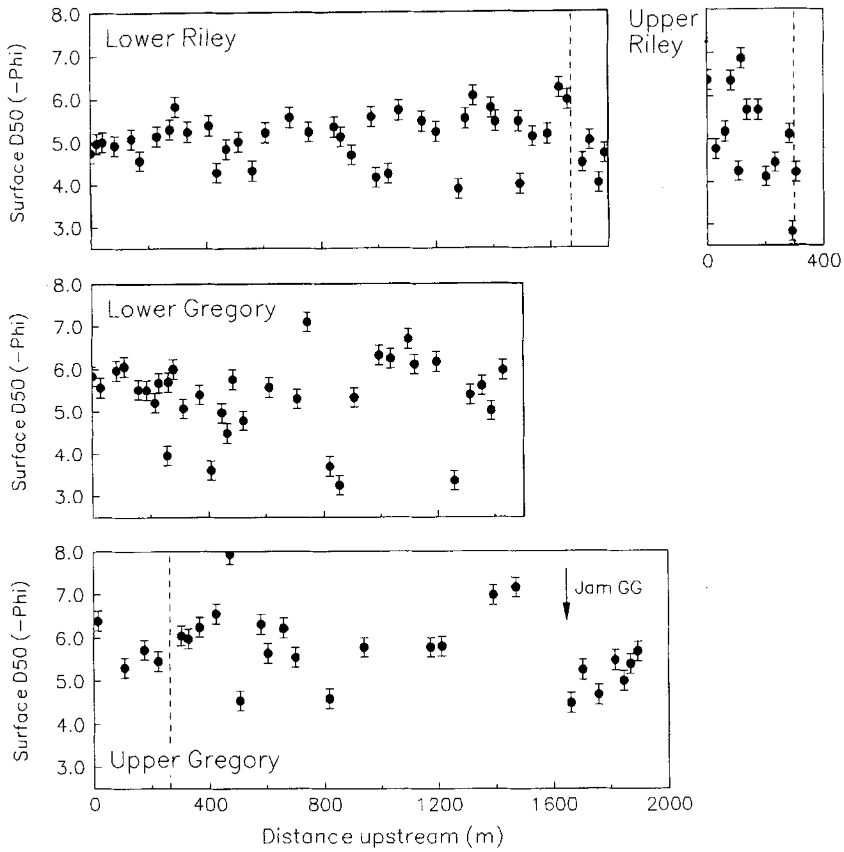

Figure 5. Photographic survey data with 95 per cent confidence limits which reflect both calibration and within-site errors. An exponential series would be indicated by a linear trend. Vertical lines denote blue-line tributaries

this section). One therefore expects to find a lower level of variability in lower Riley, and there is some evidence of this in Figure 5.

The photographic data are used in this analysis because they provide higher degrees of freedom for the statistical tests. The Lower Riley photographic reach is nested within the decoupled portion of the stream (Figure 2), and the surface D_{50} estimates have a variance of 0·329 phi units. Lower Gregory, Upper Gregory and Upper Riley lie within coupled sections, and have variances of 0·844, 0·659 and 1·258 phi, respectively. A summary of the analysis is given in Table II.

Table II. Comparison of photo reach variances (phi units)†

	Decoupled reach			Coupled reach		
	LR/UR	LR/LG	LR/UG	UR/LG	UR/UG	LG/UG
F_{calc}	3·82***	2·57***	2·00**	1·49	1·91*	1·28
d.f.	(12,41)	(33,41)	(26,41)	(12,33)	(12,26)	(33,26)

† LR = Lower Riley, UR = Upper Riley, LG = Lower Gregory, UG = Upper Gregory. Variances are significantly different when accompanied by one or more asterisks, as in Table I.

Even with statistical power biased strongly in favour of the null hypothesis ($\alpha = 0{\cdot}01$), the textural variation in Lower Riley is significantly less than that in the coupled reach upstream. It is also significantly less than in Lower Gregory and Upper Gregory. There is marginal to no significant difference amongst the coupled reaches. In general then, variance of surface median grain size is consistent in the coupled reaches and significantly larger than that in the decoupled reach. The comparison with Lower Gregory indicates that the distal position of Lower Riley is not an important factor in the reduced variability of its sediment texture.

These results are consistent with the argument that colluvial inputs are causes of significant textural perturbation. The subdued variance in Lower Riley represents the residual scatter once coupling effects are eliminated. It presumably indicates the effect on sediment texture of local sorting around log jams.

The effects of LOD on texture

Erratic fluctuations in grain size are visibly associated with LOD in streams on the Queen Charlotte Islands. This observation was first made by Hogan (1986), and incorporated into his model of log jam influence (Hogan, 1989). It is possible to suggest *a priori* how bed material texture is affected in the vicinity of a log jam. In the most simple case a log jam acts as a dam which is impermeable to sediment. This leads to aggradation and a reduction in local channel gradient upstream. Entrapment of material prevents resupply of the mobile fractions to the bed downstream and, supposing that size-selective transport occurs, relative coarsening will occur there. Upstream the most mobile fractions constitute the majority of trapped material and, consequently, relative fining will occur there. The ambient rate of sediment transport and the stability and longevity of the jam will be important determinants of the magnitude of the upstream/downstream contrast in grain size.

Log jams commonly form and disintegrate on timescales of up to 60 years in the Queen Charlotte Islands (Hogan, 1989). An initially impermeable jam becomes increasingly permeable with time as its integrity (strength) and the proportion of the channel width it occupies (span) decrease, while the number of breaching channels increases. In turn, the upstream sediment accumulation bleeds downstream and the grain size disparity is moderated. Log jams therefore have a variable effect depending on their size and age (Hogan, 1989).

These relations between jam characteristics, sediment permeability and grain-size characteristics were investigated by the detailed studies around log jams. The three jams chosen represent three levels of permeability. Jam U is less than five years old and is highly impermeable to sediment. It spans the full channel, is very strong, and is breached by two relatively small channels. Upstream the channel is filled with sediment to the height of the jam (approximately 3 m) across the full channel width (approximately 10 m). This wedge extends some 50 m upstream. In contrast, Jam N is between 30 and 50 years old and highly permeable. Although it spans three-quarters of the channel width, it is undercut by three channels and is of low integrity. Upstream, the active channel is approximately 2·5 m below the uppermost bar surfaces, indicating incision of a previous sediment accumulation. An estimated 25 to 50 per cent of the sediment once stored there has been remobilized. Jam K represents a condition between the high permeability of N and the low permeability of U. It is slightly older than jam U, but is weaker and has lost more of its sediment accumulation (up to 25 per cent).

Tracer stones were recovered at U and N one year after their deployment. Particle displacements are shown in Figure 6. In both cases, approximately 60 per cent of those placed downstream and 40 per cent of those placed upstream were recovered. The remainder were presumably lost in the jams, buried deeper than approximately 60 cm (limit of recovery depth) or moved more than 100 m beyond the downstream deployment line (limit of downstream search).

At jam N a relatively active sediment transport regime is indicated by the movement of a large proportion of the particles deployed downstream of the jam into a bar some 90 m downstream of their original position. At jam U a greater proportion of the downstream deployment remained in their original positions, suggesting a less active bed, but some particles did move as much as 90 m downstream. At jam N all but two of the particles deployed upstream of the jam were found to have moved from their original positions. Those which were recovered were spread along the downstream reach, as much as 190 m downstream of the jam. In

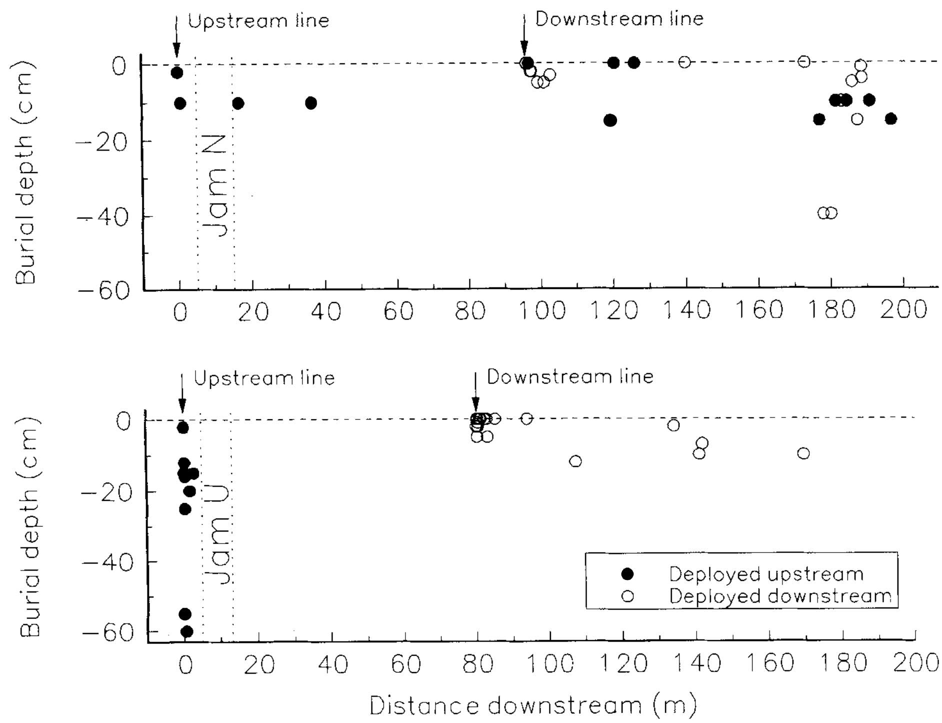

Figure 6. Tracer stone displacements. Note the permeability of jam N in contrast to the impermeability of jam U

contrast, none of the stones placed upstream of jam U were found downstream of the jam. All of the stones which were recovered were found in their original positions, buried by between 2 and 60 cm of sand and gravel.

Of the 16 scour chains, five were found broken and four were not accounted for. At jam U one chain was recovered intact from its position 15 m upstream of the jam. It recorded net fill of 22 cm which, along with the *in situ* burial of many of the tracer particles, reflects the aggradation at this site and the impermeability of the jam. Upstream of Jam N three chains, each 1·8 m long, had been scoured out completely. A fourth, 10 m upstream of the others, recorded net fill of 10 cm. Two chains recovered downstream of N recorded net scour of 5 cm (one or two particle diameters) and net fill of 25 cm. The balance of this evidence suggests upstream degradation and downstream aggradation at jam N, consistent with the redistribution of sediment through this older, more permeable jam.

In spite of the low recovery rates of both tracers and scour chains, the data which are available consistently indicate the greater permeability of jam N. The contrast in relative tracer displacements upstream and downstream suggests that, while transport through jam N is in keeping with local rates, transport through U is significantly less than normal.

Sediment samples collected upstream and downstream of the three jams reflect these differences in permeability. At jams U and K the downstream sediments are considerably coarser than those upstream, while at jam N the surface grain size distributions are very similar (Figure 7). Survey photographs upstream and downstream of jam U and general views of jam K illustrate this point (Figure 8). The pattern of upstream fining and downstream coarsening at low permeability jams was observed elsewhere along both streams. In the most extreme case encountered a single jam, approximately 7 m high and spanning a 15 m wide channel, holds back a wedge of dominantly fine sediment (surface $D_{50} = 28{\cdot}6$ mm) some 200 m long. The channel downstream is severely degraded and characterized by long bedrock stretches and sparse but coarse sediment accumulations. The initial survey samples yielded surface D_{50} values of 152 and 187 mm, 405

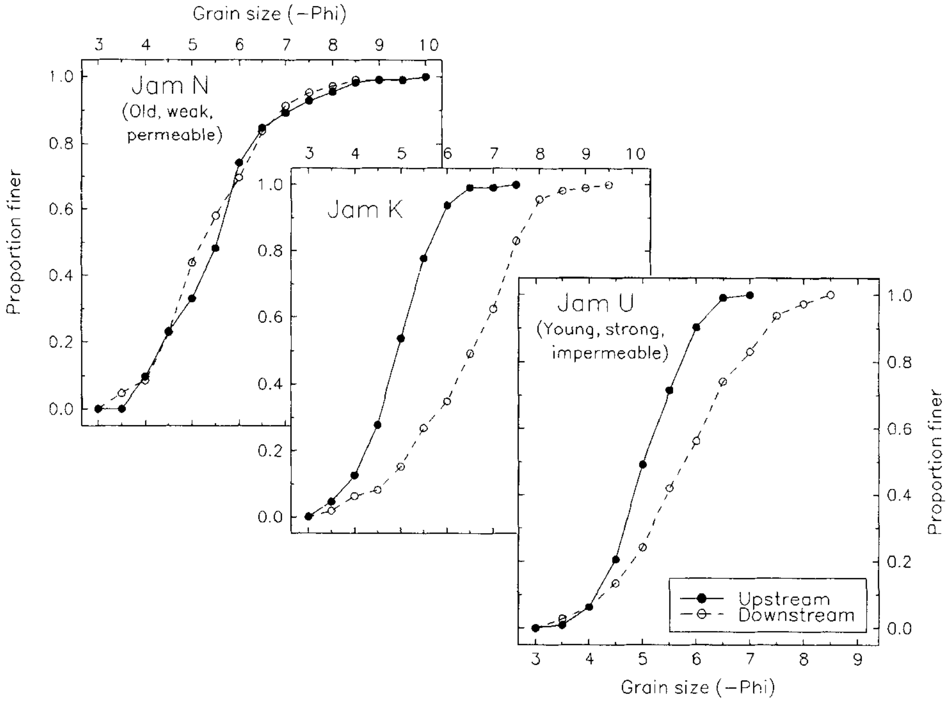

Figure 7. Surface grain size distributions upstream and downstream of the study jams

and 875 m downstream of the jam, respectively, although limited accumulations of finer material are evident intermittently in the photographic data. The location of this jam (GG) is indicated on the Upper Gregory photographic data plot (Figure 5).

These observations appear to confirm the proposal that jams which are relatively impermeable to sediment exhibit relatively coarse sediments downstream and relatively fine sediments upstream. The generality of this result was tested by examining the closest samples upstream and downstream of each of the 60 log jams encountered in the photographic survey reaches. For each jam the upstream and downstream sizes were normalized by the mean size of the pair, such that the coarser of the two would attain a normalized value, $G > 1{\cdot}0$, and the finer size a normalized value, $G < 1{\cdot}0$. A composite span and integrity index (SI) was used to stratify the data according to jam permeability. This is a semi-quantitative index in which the minimum value, $SI = 2$, indicates a strong jam spanning the whole channel width, and the maximum value, $SI = 10$, indicates an accumulation of small, unanchored pieces which span less than one-quarter of the channel width. The impact of a jam on sediment texture is therefore expected to increase as SI decreases.

In Figure 9, values of G for the 60 jams classified by SI are plotted against distance upstream ($+L$) and distance downstream ($-L$). The two strongest jams ($SI \leqslant 4$) exhibit the expected pattern, with $G > 1{\cdot}0$ when $L < 0$. However, only 62 per cent of those which have SI values of 5 and 6 exhibit finer upstream sediments. The lack of a more consistent pattern may reflect the categorization of permeability using the SI index, which can only be regarded as a first approximation. In addition, jam spacing approaches that of bar (and therefore sample) spacing in these reaches, so that the downstream effects of one jam are confounded by the upstream effects of its downstream neighbour. Thus, at the reach scale, only those jams which are highly impermeable and/or widely spaced are likely to exhibit the anticipated textural pattern.

For the more permeable jams the prevalence of fine upstream sediments and coarse downstream sediments

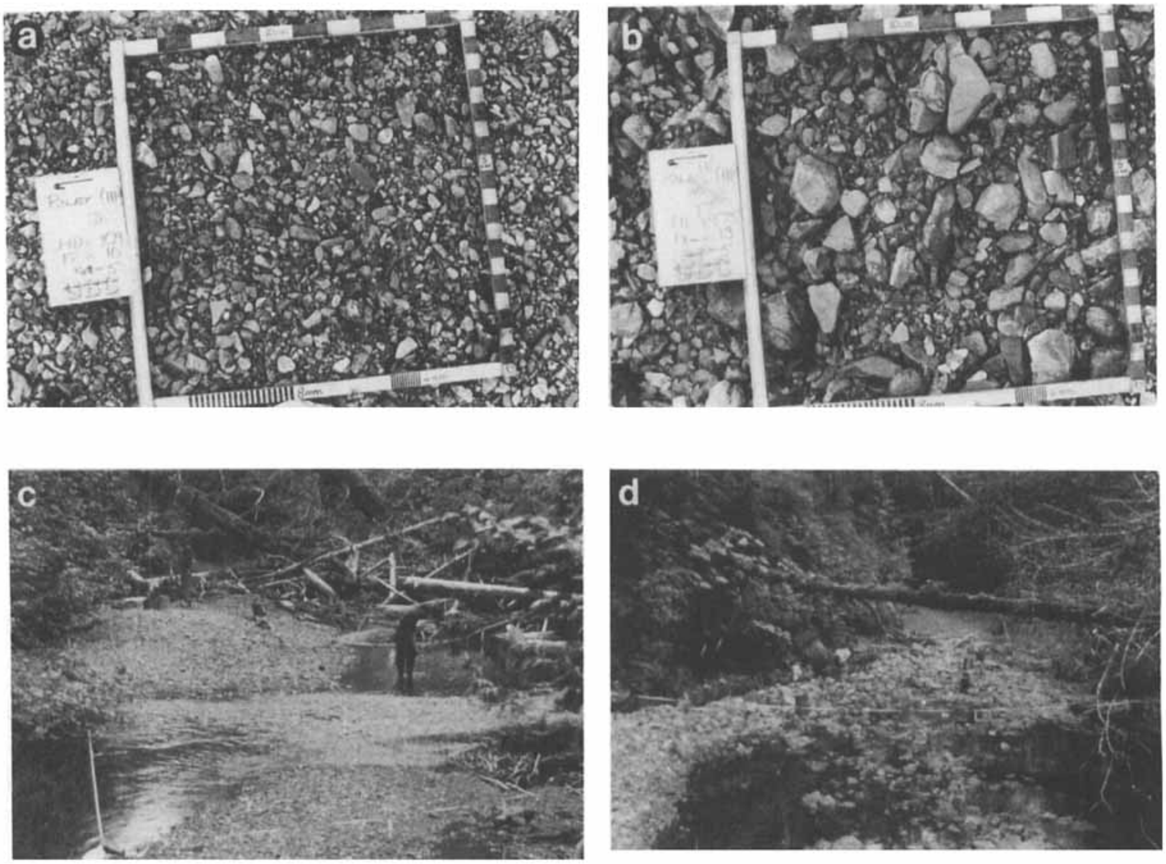

Figure 8. Log jams and bed material texture. Survey photographs of the bed surface (a) upstream and (b) downstream of jam U. General views of the bed material (c) upstream and (d) downstream of jam K

is expected to decline. While scatter is again significant, there is in fact a tendency toward a reversal of the pattern observed at the less permeable jams. Bed material is finer downstream in 70 per cent ($7 < SI < 8$) and 53 per cent ($9 < SI < 10$) of cases, which may reflect upstream degradation and the propagation of finer eroded materials through the downstream reach.

In summary, individual log jams can, depending on permeability, have a major impact on local sediment texture. They are undoubtedly the dominant cause of textural variation in these streams. Young, impermeable jams are associated with upstream fining and downstream coarsening. Older, weaker jams exhibit a reduced or even inverted disparity in grain size. The confounding effects of closely spaced jams preclude the development of consistent relations between grain size and jam proximity, as indicated by the scatter in Figure 9, which may also reflect the difficulty of quantifying jam function. At the reach scale the different ages and trap efficiencies of the jams, and the interactions of consecutive jams as they are arranged along the channel, produce complex longitudinal changes in grain size.

AN ALTERNATIVE MODEL OF TEXTURAL VARIATION

It has been shown that bed material texture varies significantly and erratically as a direct consequence of non-alluvial storage elements and colluvial inputs. The observed patterns of textural variation suggest that the spatial variation of bed material size is a stochastic phenomenon. Runs tests (Bradley, 1968)

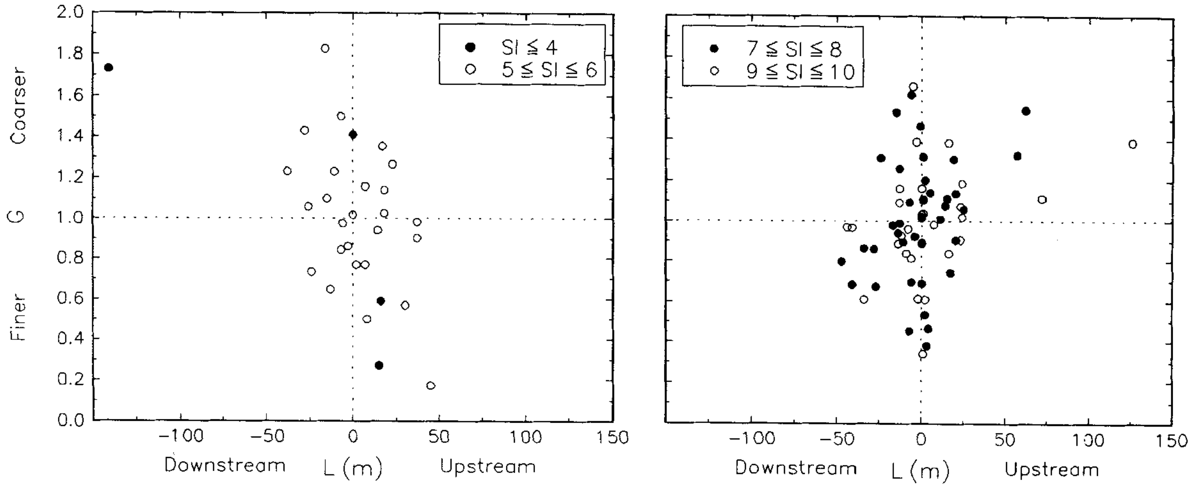

Figure 9. Normalized grain size (G) and distance upstream and downstream (L) of jams classified by span and integrity index (SI). See text for details

were applied to the initial survey and photographic survey data in order to assess the randomness of median surface size. The number of runs (an unbroken sequence of increasing or decreasing values) within a sequence of n data can be used to test its randomness. A small number of runs indicates systematic behaviour in the variate. Alternatively, a very high number of runs reflects oscillatory behaviour of a frequency approaching that of the sampling, and is also non-random. A random process will tend to produce a number which is neither very large nor very small relative to the possible number $(n-1)$ of runs. The runs test makes no distribution assumptions about the data. Tables in Bradley (1968) provide the probability that, for a given number of observations, the total number of runs will be r or fewer (where r is the observed number of runs).

For the initial survey data of Gregory, and the coupled part and decoupled part of Riley, the surface median grain sizes were classified into runs, and the number of runs counted. The results are summarized in Table III. The moderate values of p (the probability of getting r or fewer runs) for both sections of Riley suggest that there is no structure in these sets. However, the relatively high value of p for Gregory suggests that there may be some high frequency structure present. Further examination is possible using the photographic data which document grain size variations at a bar-to-bar scale. Summary results are shown in Table IV.

All four reaches are characterized by random variations in surface D_{50} between successive bars. Although insignificant statistically, there is a tendency toward high frequency behaviour in the coupled reaches (Upper Riley, Lower Gregory, Upper Gregory) and more systematic behaviour in the decoupled reach

Table III. Runs tests (low frequency)

Parameter*	Riley (decoupled)	Riley(coupled)	Gregory
n	9	9	12
r	6	6	9
p	0·7563	0·7563	0·9179
$1-p$	0·2437	0·2437	0·0821

* n is number of observations, r is the number of runs, and p is the probability of getting r or fewer runs. Values of p which exceed 0·95, or are less than 0·05, entail acceptance of H_1 (non-random generation) at $\alpha = 0{\cdot}10$

Table IV. Runs tests (high frequency)

Parameter*	Lower Riley	Upper Riley	Lower Gregory	Upper Gregory
n	41	12	34	27
r	26	8	26	20
p	0·3520	0·7280	0·9370	0·8643
$1-p$	0·6480	0·2720	0·0630	0·1357
$H_{0(0\cdot01)}$	20 to 34	4 to 10	16 to 29	12 to 23
$H_{0(0\cdot05)}$	22 to 32	5 to 9	18 to 27	14 to 22
$H_{0(0\cdot10)}$	23 to 31	5 to 9	18 to 26	14 to 21

* n is number of observations, r is the number of runs observed, p is the probability of getting r or fewer runs, and $H_{0(\alpha)}$ defines the range of r for which H_0 (random generation) is accepted at the given level of significance. For Lower Riley, Upper Gregory and Lower Gregory the values of p and critical regions of r were calculated on the basis that for $n > 25$, r asymptotically approximates a normal distribution under H_0 (see Bradley (1968) or Neter *et al.* (1982) for details). In the case of Lower Gregory, H_1 is almost accepted with $\alpha = 0{\cdot}10$ (the limit of $r = 26$ is inclusive such that H_0 is accepted ($p < 0{\cdot}95$)).

(Lower Riley). This is consistent with our contention that greater textural variability is associated with coupling.

CONCLUSION

As our original hypothesis suggested, the exponential model is of little value in the two streams studied. Surface grain size varies stochastically as a consequence of the recurrent disruption of longitudinal sediment transport by large organic debris and the sporadic contamination of the fluvial sediment population by colluvial material. The significantly higher variance of surface texture in the strongly coupled reaches confirms the role of non-alluvial inputs, while the residual, but still significant, variance in the decoupled portion of Riley highlights the impact of LOD. Both non-alluvial inputs and non-alluvially conditioned storage are important in suppressing the development of persistent textural trends, a finding not made explicit in previous studies.

Krumbein (1942) identified consistent patterns of textural variation upstream of 'log and boulder jams' in the San Gabriel mountains of southern California. Upstream, he documented a general coarsening of sediment in a downstream direction, culminating in a bouldery deposit at the jam. This reverse size gradient was not observed upstream of any of the log jams encountered in this study. Krumbein did not pursue an adequate explanation of the phenomenon, but as Carling (1987) has suggested, Krumbein's descriptions, photographs and diagrams of these 'log and boulder jams' identify several sedimentological and morphological features which are characteristic of debris flow deposits (inverse grading, matrix-supported clasts, bouldery snout and surface). Although debris flows are common in our study basins—indeed they are the dominant mechanism for delivery of sediments and LOD into the mainstem channels from steep tributaries—the debris flows do not often travel along Riley or Gregory Creeks. Rather, most log jams are formed by the fluvial rearrangement of instream LOD pieces, and subsequently become sediment traps. The log jams and associated sediments discussed in this paper are formed in a manner distinct from the 'log and boulder jams' described by Krumbein (1942).

Isolated log jams exhibit characteristic patterns of sedimentation which depend upon their age and integrity. In the vicinity of young, impermeable jams, bed material texture initially coarsens downstream and becomes finer upstream as the most mobile fractions of the bed load are trapped. With time, as the jam weakens and sediment throughput increases, this effect is moderated and may be reversed. Jams are seldom isolated, however, and the upstream effect of one jam tends to be confounded by the downstream effect of its upstream neighbour. Furthermore, each jam in a longitudinal sequence has a variable effect, largely as a function of its age, which is independent of position. Consequently, the grain size variations

associated with a series of log jams arranged along a channel are complex, and no simple structure is apparent.

As with other non-alluvial storage elements, the overall significance of LOD is expected to decline in a downstream direction as bankfull width increases relative to average tree height (cf. Church, 1993). The inability of fallen (and possibly broken) logs to span the channel and the ability of the stream to float them away will both increase as a function of increasing discharge. However, regional variations in tree height and in downstream increase of discharge relations make generalizations difficult. In Lookout Creek, Oregon, Nakamura and Swanson (1993) found that the impact of LOD on channel morphology and sediment storage was most significant in third- and fourth-order streams with average channel widths of between 15 and 18 m. In a fifth-order basin with an average width of 24 m, the impact of LOD on sediment storage was reduced. Average bankfull width in lower Riley is 41 m, yet LOD remains the dominant control of channel morphology and sediment storage.

We propose that in low-order channels, grain size change at the bar-to-bar scale is best modelled as a stochastic phenomenon. However, the absolute variations of surface D_{50} identified in this study are not necessarily transferable. The degree of coupling, and the age distribution and spacing characteristics of the log jams, are the prime determinants of the variability observed here. The nature and importance of each of these factors is expected to vary in response to differences in basin morphometry, geomorphological history, vegetation characteristics, land use history, singular hydro-meteorological events, and the passage of time. Additional observations are required in order to determine the sensitivity of textural variance to these variables.

Because low-order links are most prevalent in the landscape, a large proportion of the links in any drainage basin are expected to exhibit the stochasticity identified here. Grain size variations in higher order links will become increasingly systematic as coupling becomes intermittent and non-alluvial elements diminish in importance. Fluvial processes then dominate within links, and perturbations are increasingly associated with sediment and water inputs at network nodes. Network topology then becomes an important factor (Pizzuto, 1991). A basin-scale model which attempts to incorporate these differences is under examination (see Rice, 1994).

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REFERENCES

Alley, N. F. and Thompson, B. 1978. 'Aspects of environmental geology, parts of Graham Island, Queen Charlotte Islands, British Columbia', *British Columbia Ministry of Environment, Resource Analysis Branch Bulletin*, **2,** 65 pp.

Benda, L. 1990. 'The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA', *Earth Surface Processes and Landforms*, **15,** 457–466.

Beschta, R. L. and Platts, W. S. 1986. 'Significance and function of morphologic features of small streams', *Water Resources Bulletin*, **22,** 369–380.

Bilby, R. E. and Ward, J. W. 1989. 'Changes in characteristics and function of woody debris with increasing size of streams in Western Washington', *Transactions of the American Fisheries Society*, **118,** 368–378.

Bradley, J. V. 1968. *Distribution Free Statistics*, Prentice Hall, New Jersey, 271–281.

Bray, D. I. 1972. *Generalised regime-type analysis of Alberta Rivers*, Ph.D. thesis, University of Alberta Department of Civil Engineering, 234 pp.

Carling, P. A. 1987. 'A terminal debris-flow lobe in the northern Pennines', *Trans. Royal Soc.* Edinburgh, **78,** 169–176.

Carling, P. A. 1989. 'Hydrodynamic models of boulder-berm deposition', *Geomorphology*, **2,** 319–340.

Church, M. 1983. *Concepts of sediment transfer and transport on the Queen Charlotte Islands*, British Columbia Ministry of Forests, Fish/Forestry Interaction Program, Working paper, **2/83,** 35 pp.

Church, M. 1993. 'Channel morphology and typology', In Calow, P. and Petts, G.E. (Eds), *The Rivers Handbook, Hydrological and Ecological Principles*, Blackwell, Oxford, 126–143.

Church, M. and Kellerhals, R. 1978. 'On the statistics of grain size variation along a gravel river', *Canadian Journal of Earth Science*, **15,** 1151–1160.

Church, M., McLean, D. and Wolcott, J. F. 1987. 'River bed gravels: sampling and analysis', in Thorne, C. R., Bathhurst, J. C. and Hey, R. W. (Eds), *Sediment Transport in Gravel Bed Rivers*, Wiley, Chichester, 43–79.

Furbish, D. J. 1993. 'Flow structure in a bouldery mountain stream with complex bed topography', *Water Resources Research*, **29,** 2249–2263.

Gimbarzevsky, P. 1986. *Regional inventory of mass wasting on the Queen Charlotte Islands*, British Columbia Ministry of Forests, Land Management Report, **29,** 96 pp.

Harvey, A. M. 1987. 'Sediment supply to upland streams, influence on channel adjustment', In Thorne, C. R., Bathhurst, J. C. and Hey, R. W. (Eds), *Sediment Transport in Gravel Bed Rivers*, Wiley, Chichester, 121–150.

Harvey, A. M. 1991. 'The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, northwest England', *Earth Surface Processes and Landforms*, **16,** 675–684.

Hassan, M. A. Schick, A. P. and Laronne, J. B. 1984. 'The recovery of flood dispersed coarse sediment particles, a three-dimensional magnetic tracing method', in Schick, A. P. (Ed.), *Channel Processes–Water, Sediment and Catchment Controls, Catena Supplement*, **5,** 153–162.

Heede B. H. 1972. *Flow and channel characteristics of two high mountain streams*, USDA Forest Service Research Paper, **RM-96,** Rocky Mountain Forest and Range Experiment Station, 13 pp.

Hogan, D. L. 1986. *Channel morphology of logged, unlogged and debris torrented streams in the Queen Charlotte Islands, British Columbia*, British Columbia Ministry of Forests, Land Management Report **29,** 96 pp.

Hogan, D. L. 1989. 'Channel responses to mass wasting inputs, Queen Charlotte Islands, British Columbia', *Watershed '89: A conference on the stewardship of soil, air and water resources, Juneau, Alaska*, U.S. Dept Agriculture Forest Service, Alaska region, 22 pp.

Horton, R. E. 1945. 'Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology', *Geological Society of America Bulletin*, **56,** 275–370.

Keller, E. A and Swanson, F. J. 1979. 'Effects of large organic material on channel form and fluvial processes', *Earth Surface Processes and Landforms*, **4,** 361–380.

Kellerhals, R. and Bray, D. I. 1971. 'Sampling procedures for coarse fluvial sediments', *American Society of Civil Engineers, Journal of Hydraulic Engineering*, **97,** 1165–1180.

Knighton, A. D. 1975. 'Channel gradient in relation to discharge and bed material characteristics', *Catena*, **2,** 263–274.

Knighton, A. D. 1980. 'Longitudinal changes in size and sorting of stream bed material in four English Rivers', *Geological Society of America Bulletin*, **91,** 55–62.

Krumbein, W. C. 1942. 'Flood deposits of the Arroyo Seco, Los Angeles County, California', *Geological Society of America Bulletin*, **53,** 1355–1402.

Lisle, T. E. 1986. 'Stabilisation of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California', *Geological Society of America Bulletin*, **97,** 999–1011.

Lisle, T. E. 1987. 'Channel morphology and sediment transport in steepland streams', in *Erosion and Sedimentation in the Pacific Rim*, Proceedings of the Corvallis Symposium, August 1987, IAHS Publication No. **165,** 287–297.

Lisle, T. E. and Kelsey, H. M. 1982. 'Effects of large roughness elements on the thalweg course and pool spacing', in Leopold, L. B. (Ed.), *American Geomorphological Field Group Guidebook, Pinedale, Wyoming*, American Geophysical Union, Berkeley, California.

MacPherson, H. J. 1971. 'Downstream changes in sediment character in a high energy mountain stream channel', *Arctic and Alpine Research*, **3,** 65–79.

Mikos, M. 1993. 'Fluvial abrasion of gravel sediments', *Mitteilungen*, **123,** Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie der Eidgenossischen Technischen Hochschule, Zurich, 322 pp.

Miller, J. P. 1958. *High Mountain Streams: effects of geology on channel characteristics and bed material*, Memoir 4, State Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, New Mexico, 53 pp.

Nakamura, F. and Swanson, F. J. 1993. 'Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon', *Earth Surface Processes and Landforms*, **18,** 43–61.

Neter, J., Wasserman, W. and Whitmore, G. A. 1982. *Applied Statistics*, (2nd edn), Allyn and Bacon, Boston, 394–398.

Newson, M. J. 1981. 'Mountain streams', in Lewin, J. (Ed.), *British Rivers*, George Allen and Unwin, London, 59–89.

O'Connor, J. E., Webb, R. H. and Baker, V. R. 1986. 'Paleohydrology of pool-riffle pattern development: Boulder Creek, Utah', *Geological Society of America Bulletin*, **97,** 410–420

Parker, G. 1991. 'Selective sorting and abrasion of river gravels I: theory', *American Society of Civil Engineers, Journal of Hydraulic Engineering*, **117,** 131–149.

Pizzuto, J. E. 1991. 'Interpreting the pattern of downstream fining in a network: Why process is insignificant', *EOS Supplement, AGU Spring Meeting Program and Abstracts 1991*, 134

Rice, S. P. 1994. 'Towards a model of bed material texture at the drainage basin scale', in Kirkby, M. J. (Ed.) *Process Models and Theoretical Geomorphology*, Wiley, Chichester, 159–172.

Rice, S. P. (1995). *The spatial variation and routine sampling of spawning gravels in small coastal streams*, British Columbia Ministry of Forests, Working Paper 06/1995.

Roberts, R. G. 1987. *Stream channel morphology: major fluvial disturbances in logged watersheds on the Queen Charlotte Islands*, British Columbia Ministry of Forests, Land Management Report, **48,** 69 pp.

Roberts, R. G. and Church, M. 1986. 'The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia', *Canadian Journal of Forest Research*, **16,** 1092–1106.

Rood, K. M. 1984. *An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia*, British Columbia Ministry of Forests, Land Management Report **35,** 55pp.

Schwab, J. W. 1983. 'Mass wasting: October–November 1978 storm, Rennell Sound, Queen Charlotte Islands, British Columbia', *British Columbia Ministry of Forests Research Note*, **91,** 23 pp.

Shaw, J. and Kellerhals, R. 1982. 'The composition of recent alluvial gravels in Alberta river beds', *Alberta Research Council Bulletin*, **41,** 151 pp.

Shreve, R. L. 1966. 'Statistical law of stream numbers', *Journal of Geology*, **74,** 17–37.

Sternberg, H. 1875. 'Untersuchungen uber Langen–und Querprofil geschiebefuhrender', *Zeitschrift fur Bauwesen*, **25,** 483–506.

Sutherland Brown, A. 1968. 'Geology of the Queen Charlotte Islands, British Columbia', *British Columbia Department of Mines and Petroleum Resources, Bulletin*, **54,** 226 pp.

Swanson, F. J., Lienkaemper, G. W. and Sedell, J. R. 1976. *History, physical effects, and management implications of large organic debris in western Oregon streams*, USDA Forest Service General Technical Report, **PNW-GTR-56,** Pacific Northwest Forest and Range Experiment Station, 15 pp.

Swanston, D. N. and Swanson, F. J. 1976. 'Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest', in Coates, D. R. (Ed.), *Geomorphology and Engineering*, Dowden, Hutchinson and Ross, Stroudsberg, Pennsylvania, 199–221.

Werrity, A. 1992. 'Downstream fining in a gravel bed river in southern Poland: Lithological controls and the role of abrasion', In Billi, P. *et al.* (Eds), *Dynamics in Gravel Bed Rivers*, Wiley, Chichester, 333–346.

Whiting, P. J. and Bradley, J. B. 1993. 'A process-based classification system for headwater streams', *Earth Surface Processes and Landforms*, **18,** 603–612.

Wolcott, J. F. and Church, M. 1991. 'Strategies for sampling spatially heterogeneous phenomena: the example of river gravels', *Journal of Sedimentary Petrology*, **61,** 534–543.

Wolman, M. G. 1954. 'A method of sampling coarse river bed materials', *American Geophysical Union Transactions*, **35,** 951–956.